

# The Supernova Remnant G11.2–0.3 and its central Pulsar

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## ABSTRACT

The plerion inside the composite Supernova Remnant G11.2–0.3 appears to be dominated by the magnetic field to an extent unprecedented among well known cases. We discuss its evolution as determined by a central pulsar and the interaction with the surrounding thermal remnant, which in turn interacts with the ambient medium. We find that a plausible scenario exists, where all the observations can be reproduced with rather typical values for the parameters of the system; we also obtain the most likely period for the still undetected pulsar.

*Subject headings:* ISM: Supernova Remnants — ISM: Individual: G11.2–0.3 — Stars: Pulsars: General

## 1. Introduction

Vasisht et al. (1996, hereafter VA) have recently discussed the nature of the remnant G11.2–0.3 (Historical Supernova 386 AD) and have shown that it is likely to be of a composite nature, as already suggested on the basis of radio data by Morsi & Reich (1987). The hard X-ray emission observed by ASCA, combined with previous Einstein data and observations at other wavelengths, strongly suggests (despite the fact that a pulsar has not yet been discovered) the presence of a plerion surrounded by a thermal shell. The data across the electromagnetic spectrum can then be combined with the theory of the evolution of pulsar-powered remnants (Pacini & Salvati 1973 (PS); Bandiera, Pacini & Salvati 1984; Reynold & Chevalier 1984) and allow a determination of the physical parameters of the system. The main outcome of the interpretation proposed by VA is that the plerion should be characterized by a magnetic energy much higher than the energy channelled into relativistic electrons, at variance with, e.g., the Crab Nebula.

In our paper we study the evolution of the plerion coupled with that of the surrounding shell. We show that the magnetic field determination of VA is only marginally consistent, from a dynamical point of view, if the thermal and non-thermal remnants are in pressure equilibrium. We identify, on the other hand, a scenario that is in agreement with the observations, and derive the initial and present parameters of the central pulsar. In particular, we show that the apparent preponderance of the magnetic component in the pulsar output may be a natural outcome of the evolution, and does not imply a strong unbalance in the mechanism of production.

Following VA we assume that G11.2–0.3 is the remnant of SN 386 AD and therefore has an age  $t = 1610 \text{ yr} = 5 \times 10^{10} \text{ s}$ . For its distance we use a reference value of 5 kpc and define  $d_5 = d/(5 \text{ kpc})$ . The outer thermal shell has radius  $R_s = 3.3 d_5 \text{ pc}$ , electron temperature  $T_s = 0.73 \text{ keV} = 8.5 \times 10^6 \text{ K}$ , X-ray luminosity  $L_s \sim 10^{36} d_5^2 \text{ erg s}^{-1}$  (in the 0.6–3.3 keV

band), from which VA derive an ambient density  $n_o \sim 1.5 d_5^{-1/2} \text{ cm}^{-3}$ , by assuming a Sedov (1959) expansion in the interstellar medium. The central plerionic component has a radius  $R_p \sim 1 d_5 \text{ pc}$  and its spectrum is equal to

$$L_\nu \simeq 3 \times 10^{16} \left( \frac{\nu}{2.5 \times 10^{18} \text{ Hz}} \right)^{-0.8} d_5^2 \text{ erg s}^{-1} \text{ Hz}^{-1}, \quad (1)$$

corresponding to an X-ray luminosity  $L_p \simeq 1 \times 10^{35} d_5^2 \text{ erg s}^{-1}$ , in the 0.5–4 keV band. eq. (1) is consistent with the observations down to 32 GHz, but overestimates the plerion emission at 1 GHz. Accordingly, the spectrum must have a break at a frequency  $\nu_o$  between 1 GHz and 32 GHz.

## 2. The model

The assumption of the PS model is that the central pulsar feeds both magnetic field and relativistic particles into the expanding plerion. Taking into account the adiabatic losses and the rate of production, the evolution of the field strength is given by

$$\frac{d}{dt} \left( \frac{B^2 R_p^4}{6} \right) = p \dot{\mathcal{E}} R_p. \quad (2)$$

Here  $p$  is the fraction of the pulsar energy loss  $\dot{\mathcal{E}}$  that goes into magnetic energy; it is assumed that  $p$  is constant. According to standard pulsar electrodynamics  $\dot{\Omega} \propto -\Omega^n$ , with  $n$  being the so-called braking index, and

$$\dot{\mathcal{E}} = \frac{\dot{\mathcal{E}}_o}{(1 + t/\tau_o)^\alpha}, \quad (3)$$

with  $\alpha = (n + 1)/(n - 1) = 2$  in a pure dipole field. Measured values of  $n$  range roughly between 1.4 for the Vela pulsar (Lyne, private communication) and 2.8 for PSR 1509-58 (Kaspi et al. 1994). The pulsar is assumed to inject also relativistic particles, whose energies are distributed according to a power law with constant index  $\gamma$ , at a rate  $(1 - p)\dot{\mathcal{E}}$ .

The evolution of the electron energies is determined by both adiabatic and synchrotron losses.

An immediate implication of the theory is that the emitted spectrum of the plerion should show a break at a frequency  $\nu_b$  such that particles radiating at  $\nu_b$  have a lifetime equal to the age of the nebula. Since  $\nu_b \propto B^{-3}t^{-2}$ , if the observed break is identified with  $\nu_b$  one directly derives the field strength in G11.2–0.3

$$B = 2.1 \times 10^{-3} \left( \frac{\nu_b}{32 \text{ GHz}} \right)^{-1/3} \text{ G}, \quad (4)$$

which corresponds to a total field energy

$$W_B = 2.1 \times 10^{49} \left( \frac{\nu_b}{32 \text{ GHz}} \right)^{-2/3} d_5^3 \text{ erg}. \quad (5)$$

The synchrotron spectrum above  $\nu_b$ , up to a maximum frequency  $\nu_{max}$ , is given by

$$L_\nu = \frac{2 - \gamma}{\gamma - 1} \frac{(1 - p)\dot{\mathcal{E}}}{2\nu_{max}} \left( \frac{\nu}{\nu_{max}} \right)^{-\gamma/2}. \quad (6)$$

From the observations  $\gamma = 1.6$  and  $\nu_{max} > 2.5 \times 10^{18} \text{ Hz}$ ; by combining eqs. (1) and (6) we find the present-time energy loss from the pulsar:

$$\dot{\mathcal{E}} = 2.24 \times 10^{35} \left( \frac{\nu_{max}}{2.5 \times 10^{18} \text{ Hz}} \right)^{0.2} \frac{d_5^2}{1 - p} \text{ erg s}^{-1}. \quad (7)$$

We describe the relative importance of the magnetic and particle components in terms of the dimensionless quantity  $Q = B^2 R_p^3 / 6(1 - p)\dot{\mathcal{E}}t$ . By substituting eq. (3) into eq. (2) and integrating, we find

$$Q = \frac{p}{1 - p} \frac{(1 + \tilde{t})^\alpha}{\tilde{t}^{1+r}} \int_0^{\tilde{t}} \frac{x^r}{(1 + x)^\alpha} dx; \quad (8)$$

here we put  $\tilde{t} = t/\tau_o$ , and assumed a power law for the expansion,  $R_p \propto t^r$ . Note that  $Q$  is a measure of the balance at production rather than a gauge of equipartition: in fact, when  $p \approx 0.5$ ,  $Q \approx 1$  until  $t \leq \tau_o$  (and later on as well if  $\alpha = 1 + r$ ). The ratio of magnetic to

particle energy, instead, can be arbitrarily high if the radiative lifetime of the energetically important particles is sufficiently shorter than  $t$ . On the observational side, eqs. (5) and (7) give

$$Q = 1860 \left( \frac{\nu_b}{32 \text{ GHz}} \right)^{-2/3} \left( \frac{\nu_{max}}{2.5 \times 10^{18} \text{ Hz}} \right)^{-0.2} d_5 : \quad (9)$$

the magnitude of  $Q$  in the present case, to be compared with  $Q \approx 1$  for the Crab plerion, is a quantitative measure of the discrepancy which we want to address. For G11.2–0.3, then, either  $p$  is very close to unity ( $1 - p < 10^{-3}$ ), or  $\tilde{t} \gg 1$ ,  $(\alpha - 1 - r) > 0$ . We regard the former possibility as very unlikely, and in the following we shall limit ourselves only the latter.

When  $t \gg \tau_o$ , it is appropriate to assume flux conservation for the evolution of the magnetic field,  $B \propto t^{-2r}$ ; furthermore, the plerion spectrum shows *two* breaks (PS), of which the higher one,  $\nu_b$ , corresponds to the radiative lifetime at the current time  $t$ , and the lower one,  $\nu_c$ , is the signature of the radiative lifetime at  $\tau_o$ . If we identify the observed break with  $\nu_b$ , eq. (4) holds, and the pressure interior to the plerion is relatively very high. As we show in the following, the magnetic pressure corresponding to eq. (4) exceeds the shell pressure by a large factor; this is possible only if the plerion expansion is limited by the inertia of some cold matter tied to the plerion itself, in which case we expect  $r \geq 1$ . Then  $r \geq 1$  and  $\alpha \leq 3$ , as observed in all measured cases, give  $p$  of order 0.5 only at the expense of  $\tilde{t} \geq 1000$ , and an initial magnetic energy of order  $\tilde{t} \times W_B > 10^{52} d_5^3$  erg. We consider very unlikely a value so much larger than the canonical supernova output, and propose that: *i*) the plerion and the shell are in pressure equilibrium, so that  $r < 1$ ; and *ii*) the observed break is to be identified with  $\nu_c$ , so that  $\nu_b = \nu_c \times \tilde{t}^{10r-2} \gg \nu_o$ , and  $Q$  is decreased with respect to eq. (9). However, the break at  $\nu_b$  entails a change of slope  $\epsilon = (2.8r - 0.4\alpha)/(5r - 1)$  (see PS); since G11.2–0.3 shows a straight spectrum from the microwaves to the X rays, we must require  $\epsilon = 0$ ,  $\alpha = 7r$ .

Within this framework more detailed results can be obtained by coupling the plerion evolution to the hydrodynamics of the thermal shell. We can distinguish two different cases, according to the distribution of the ambient density being of the interstellar type ( $\rho_o \sim \text{constant}$ , henceforth IS), or circumstellar type ( $\rho_o \sim r^{-2}$ , henceforth CS). If the ambient medium has a constant density,  $R_s \propto t^{2/5}$ ,  $R_p \propto t^{3/10}$ , and, because of the condition on  $\epsilon$ ,  $\alpha = 2.1$ . If the shell expands inside the pre-supernova wind, one has  $R_s \propto t^{2/3}$ ,  $R_p \propto t^{4/7}$ , and  $\alpha = 4.0$ .

We have computed in detail the two cases, and give the results in Table 1. In particular, we have adjusted the unknown distance  $d_5$  so as to make the total energy of the shell remnant equal to the canonical  $10^{51}$  erg. We have chosen the value of  $\nu_o$  within the allowed interval so as to bring our results as close as possible to ‘typical’ values. And, finally, we have neglected the work done by the plerion on the shell remnant, which is justified *a posteriori* by the relatively small plerion energetics resulting from the computations. The precise value of the ambient density in the IS and CS cases was computed so as to reproduce the temperature and flux of the thermal X rays given in VA.

Note that the CS assumption leads to very ‘palatable’ estimates for all the unknowns, with one exception: the slowing down exponent  $\alpha$  implies a braking index  $n = 1.67$ . We note that such value is still in the acceptable range between a purely dipolar ( $\alpha = 3$ ,  $n = 3$ ) and a purely monopolar geometry ( $\alpha = \infty$ ,  $n = 1$ ), but that for most pulsars the braking index is between 2 and 3. On the other hand, the IS hypothesis carries along some deviation from perfect balance at production ( $p \sim 0.9$ ) and a pulsar magnetic field at the extreme of the observed range ( $B_* = 1.3 \cdot 10^{13}$  G, like in PSR 1509-58). All in all, we regard the latter interpretation as the most plausible one, also because it places G11.2-0.3 exactly on the empirical relation between  $L_p$  and  $\dot{\mathcal{E}}$  given by Seward & Wang (1988); we suggest that the corresponding values in Table 1 be taken as a reasonable guess for further observing efforts.

A major improvement in the modelling could ensue if future observations were to give the precise frequency of the break(s) in the spectrum and the related change(s) of slope, or the detection of the pulsar.

### 3. Conclusions

If G11.2–03 is a composite remnant deriving from the historical explosion of SN 386 AD, the main parameters of the nebula and of the central pulsar can be estimated in the framework of the PS model. They appear to be consistent with the properties of the remnant and the standard views on pulsars.

The apparent preponderance of the magnetic channel in the output of the central pulsar is the consequence of the dynamical evolution under the influence of the external shell. This has slowed down the expansion and therefore reduced the importance of the adiabatic losses with respect to the synchrotron losses. Since most of the energy was released by the pulsar during a relatively short initial phase, it is natural that the subsequent evolution has led to a large value of  $Q$ , eq. (8), even if the pulsar output was always well balanced,  $p \approx 0.5$ . We strongly stress this point as relevant to all sorts of non-thermal sources: only if the generation of particles and fields keeps occurring for a time scale longer or roughly equal to the age of the source does  $Q$  reflect the balance at production between fields and particles. This is why  $Q \approx 1$  in the Crab plerion, for which  $t \approx 3 \times \tau_o$ . In addition, and for quite independent reasons, the Crab is not far from equipartition, since its  $\nu_b$  is not far from the frequency where most of the power is emitted.

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Table 1. Parameters of the Models

Parameter	IS Model	CS Model
$\nu_o$	4 GHz	32 GHz
$d$	9.2 kpc	7.4 kpc
$p$	0.9	0.3
$B_p$	$9.3 \times 10^{-4}$ G	$1.8 \times 10^{-4}$ G
$P$	0.34 s	2.73 s
$\dot{\mathcal{E}}$	$1.55 \times 10^{37}$ erg s $^{-1}$	$1.25 \times 10^{36}$ erg s $^{-1}$
$B_*$	$2.5 \times 10^{13}$ G	$1.6 \times 10^{12}$ G
$\tau_o$	$5.8 \times 10^8$ s	$7.0 \times 10^9$ s
$P_o$	0.029 s	0.139 s
$\mathcal{E}_o$	$2.4 \times 10^{49}$ erg	$1.0 \times 10^{48}$ erg

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